LTE vs. WiMAX - Next Generation Telecommunication Networks

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***Abstract*—This paper presents the leading technologies for the next generation wireless telecommunication networks, LTE and WiMAX. Furthermore, the used modulation and multiplexing schemes such as QPSK, QAM, OFDM, OFDMA, SC-FDMA and MIMO will be shown. In addition, the network architecture and the basic characteristics of each 4G network approach will be presented. This is followed by a discussion where use cases, deployment and power consumption will be discussed. The paper further concludes the discussion and gives a short outlook of the IMT-Advanced networks.**

***Index Terms*—LTE, WiMAX, 4G, OFDM, OFDMA**

I. Introduction

In the last two decades the growth of subscribers in telecommunication networks has been exponential. First approaches of wireless telecommunications networks in 1980s were analog (1G) and have been replaced by digital approaches. The digital wireless telecommunication networks (2G) started with a circuit-switched (CS) approach called GSM (Global System for Mobile Communication). The CS approach was well known from the fixed telephony system and allowed the compatibility of both systems. As the Internet and the Mobile Services emerged and the performance of Embedded Systems increased new services were available. The idea of bringing data transmission to mobile devices lead to the first packet-switching extension of GSM which is called GPRS (General Packet Radio Service) and further EDGE (Enhanced Data Rate for GSM Evolution). The continuous growth of subscribers lead to several GSM extensions and lead finally to UMTS (Universe Mobile Telecommunications System, also known as 3G) which was standardized by 3GPP (3rd Generation Partnership Project). UMTS required new base stations and new frequencies, which made the deployment more difficult and cost-intensive. On the other hand UMTS supports much higher data rates and enables advanced mobile services. Further evolutions of UMTS are HSDPA (High-Speed Downlink Packet Access) and HSPA(+) (High-Speed Packet Access), which supports data rates similar to fixed ADSL links.

There are also competing technologies to GSM/UMTS. The main competitor is IS-95 (also known as cdmaOne) (2G) and CDMA2000 (Code Division Multiple Access) (3G). They are also widely spread, especially in Asia and North America. GSM/UMTS and IS-95/CDMA2000 are not compatible with each other.

The Internet has shown that packet-switching telephony (e.g. VOIP, SIP) is a reliable alternative to native circuit-switched telephony. This leads to the conclusion that the complex circuit-switched core network is no longer needed. Therefore the 4th generation of mobile networks (4G) does not support any circuit-switched domain. In addition the continuous growth of mobile subscribers and data transfer shows that more advanced and efficient telecommunication networks are needed. The evolution of mobile handsets from simple phones to general purpose computers (so called Smartphones) is a key driver for the 4G networks. These mobile devices allow further mobile services that go beyond telephony and messaging. Especially new service scenarios such as IPTV, Mobile Payment or Real-time gaming require high bandwidth, very low delays and also high availability. Furthermore 4G networks can be used to bring high speed access to more rural areas which are not covered by the fixed high speed networks.

The ITU-R (International Telecommunication Union Radiocommunication Sector) has specified the IMT-Advanced (International Mobile Telecommunications Advanced) requirements for 4G standards. Nevertheless the term “4G” is widely used for advanced telecommunication networks that are based on OFDMA (Orthogonal Frequency Division Multiple Access), use MIMO (Multiple Input Multiple Output) and have an IP-only architecture.

This paper will present the two most common approaches for 4G telecommunication networks, which are LTE (Long Term Evolution) and WiMAX (Worldwide Interoperability for Microwave Access). Section II will show the techniques that both technologies use for the “air interface”. The key drivers, architecture and characteristics of LTE (section III) and WiMAX (section IV) will be presented. A discussion in section V will compare both technologies in different aspects such as scenarios, enterprise use, deployment and power consumption. Section VI will give an overview of the IMT-Advanced 4G telecommunication networks which are currently under development and look into future developments. The last section summarizes the conclusions from this paper.

II. Fundamentals of Multiplexing and Modulation

Digital wireless telecommunication networks use different modulation schemes to transfer data over the “air interface”. LTE and WiMAX use a combination of varying modulation schemes, such as QPSK (Quadrature Phase-Shift Keying) or QAM (Quadrature Amplitude Modulation), and the multiplexing schemes OFDM (Orthogonal Frequency Division Multiplexing) and MIMO (Multiple Input Multiple Output). These modulation schemes allow adaption to different demands, such as high range or high throughput. QPSK and QAM are already well known and have proven their abilities in various wireless communication technologies. OFDM is a relatively new approach for the use in digital wireless communication. The reason for choosing OFDM for the next generation networks are manifold. First implementations with relatively fixed wireless terminals (e.g. DVB-T or WLAN) have shown the good properties of OFDM. In addition, it allows a good utilization of the frequency bands. With its multi-user access extension OFDMA, OFDM is able to satisfy the requirements for an adaption in wireless telecommunication networks with multiple users. MIMO allows higher data rates with spatial multiplexing.

QPSK

QPSK is a phase-shifting modulation scheme. The carrier frequency phase is shifted to send data. With QPSK it is possible to send two symbols by shifting the frequency in four different phases (0, 90, 180, 270 degrees). Therefore the modulation scheme recognizes only phase-shifting and is not susceptible to amplitude changes by interferences.

Phase Shift	Symbol
0°	00
90°	01
180°	11
270°	10

Table I
QUADRATURE PHASE-SHIFT KEYING

QAM

QAM combines two techniques for modulation. It uses PSK (Phase-Shift Keying) and ASK (Amplitude-Shift Keying). ASK uses different frequency amplitudes to distinguish between symbols (high = 1, low = 0). Hence QAM uses amplitude and phase shifting. QAM changes the amplitude of two carrier signals, which are 90° out-of-phase with each other. By using a varying number of amplitudes and phases more symbols can be transfered. Wireless telecommunication networks widely use digital 16-QAM (16 Symbols,4 Bits) or 64-QAM (64 Symbols, 6Bits) modulation schemes. [1]

This move to higher order modulations allows higher transfer rates. However, this leads also to higher error rates and requires a higher SNR (Signal-to-Noise Ratio). As more symbols are transfered the detection of a particular symbol is more difficult and more susceptible for errors. Therefore error detection techniques while encoding and decoding the symbols is needed. Examples are Forward Error Correction (FEC) [2] which adds systematically redundant data or the Viterbi decoder [3] which uses this data to correct errors without asking for retransmission.

OFDM

OFDM is a frequency division multiplexing modulation scheme which divides the data transmission over several streams, one for each orthogonal subcarrier. For the further modulation of each orthogonal subcarrier QPSK or QAM is used. OFDM is already successfully used in wireless technologies such as WLAN, DVB-T or DAB. Additionally, it allows a large number (several hundreds) of narrow-band subcarriers. In comparison, in other multi-carrier extension such as the WCDMA (Wideband Code Division Multiple Access) multi-carrier evolution, a 20 MHz bandwidth could consist of four 5 MHz (sub)carriers. OFDM uses IFFT (Inverse Fast Fourier Transform) and FFT (Fast Fourier Transform) for the signal modulation. Figure 1 shows the OFDM spectrum with the subcarrier division and the subcarrier spacing Δf = $1/T_u$, where T_u is the per-subcarrier modulation symbol time. The subcarrier spacing can range from a few kHz up to several hundred kHz. The subcarrier spacing for 3GPP LTE is about 15 kHz, whereas WiMAX uses 11 kHz. In addition, figure 1 shows the orthogonality between the subcarriers, which allows high spectral efficiency. However, OFDM's major disadvantage is that it has a higher PAPR (Peak-to-average power ratio, also referred as the crest factor or PAR) and so a higher power consumption. The large dynamic range of OFDM signals leads to an inefficient power amplification of the transmitted signal and also increases the required resolution and power dissipation of the DAC (Digital Analog Converter) in the transmitter [4].

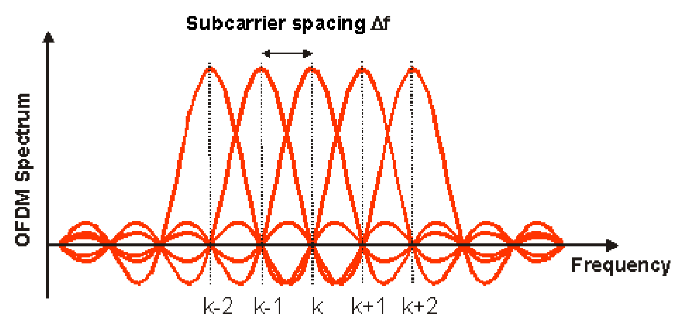

Figure 1. OFDM Spectrum [5]

OFDMA

Often OFDMA and OFDM are used as synonymous. However, OFDMA allows the use of OFDM modulation for multiple user access. To enable this, users can be allocated to any of the subcarriers in the used frequency band. In addition, this allows a flexible and therefore better scheduling of resource allocation and services. To provide a good applicability subcarriers are pooled to resource blocks (12 subcarriers per time slot). As figure 2 shows these blocks can be scheduled to different users.

Furthermore certain enhancements or variations are used in LTE and WiMAX, such as SOFDMA (Scalable OFDMA) and SC-FDMA (Single Carrier - Frequency Division Multiple Access).

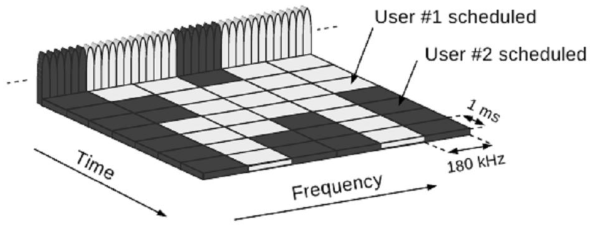

Figure 2. OFDMA Resource Block Scheduling [6]

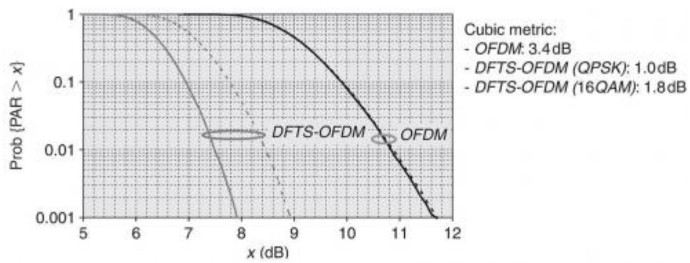

Figure 3. PAR distribution and cubic metric of OFDM and SC-FDMA (DFTS-OFDM), Solid curve: QPSK. Dashed curve: 16QAM [10]

SOFDMA

SOFDMA adds scalability support to OFDMA. Both OFDMA-based systems, LTE and WiMAX support variable bandwidth sizes. The main goal of SOFDMA is to keep the subcarrier spacing constant. Therefore it scales the FFT size with the bandwidth. This allows lower complexity of smaller bandwidth channels and improves the performance of wider bandwidth channels. Table II shows the different OFDMA scalability parameters for WiMAX and LTE. [7]

Parameters	Values				
System bandwidth (MHz)	1.25 (1.4)	(3)	5	10	20
FFT size	128	256	512	1024	2048
Subcarrier spacing	11.1607 kHz (15 kHz)				
Symbol time	89.6 µs (66.6 µs)				

Table II
OFDMA SCALABILITY PARAMETERS. IN BRACES: LTE VALUES [8], [9]

SC-FDMA

The basic drawback of OFDM is the already mentioned high power consumption. Especially in the uplink where often mobile terminals are used, the power consumption of the data transmission is very crucial. For this reason, 3GPP LTE uses Single Carrier FDMA, which is also referred as DFTS-OFDM (Discrete Fourier Transform Spread OFDM). SC-FDMA is a single carrier modulation. SC-FDMA is basically a normal OFDM with a DFT-based precoding. The main advantage of this approach is that it reduces the variations of instantaneous transmit power, which eventually implies an increas of power amplifier efficiency. Whereby SC-FDMA provides a lower PAPR of the transmitted signal. Figure 3 illustrates the distribution of the PAPR between both modulation schemes and the cubic metric, which shows the reduction of power capability. Both metrics show that SC-FDMA is superior to OFDM in terms of power consumption. With this approach LTE is able to avoid the disadvantages of OFDM in the aspect of power consumption.

MIMO

One of the fundamental technologies used in the 4G networks is MIMO (Multiple Input Multiple Output). This technology is already used in 802.11n (WLAN-n standard). The basic principle behind this technology is the spatial multiplexing. For this approach multiple antennas at the sender and the receiver side are needed. In MIMO the data stream is divided in multiple smaller data streams. These smaller data streams are then sent and received over multiple antennas. This approach takes advantage of the multi-path propagation of radio signals and the peak data rates increase, because of the multiple antennas. However, with the use of multiple antennas also the power consumption increases. There are several different configuration for MIMO. The often used terms 4x4 (4 sending antennas, 4 receiving antennas), 4x2 or 2x2 represent the MIMO configuration. Similar approaches are SIMO (Single Input Multiple Output) which is often used in battery powered User Terminals, MISO (Multiple Input Single Output) or the well known approach with one antenna on each side SISO (Single Input Single Output).

III. 3GPP LONG TERM EVOLUTION

The work on 3GPP LTE Release 8 started in 2004 [10], [11]. The development of LTE was driven by certain aspects. First, the wireline data networks improved and higher data rates were possible. This lead to new applications and services which are often referred to as the “Web 2.0”. The current approaches of UMTS/HSDPA/HSPA in 2004 were capable to deliver this first generation of Web 2.0-services. But it was obvious that these kind of services would evolve and the demands of higher bandwidth and lower delays would grow. Second, to cover the mentioned tremendous growth of mobile subscribers new technologies that are specifically designed for higher capacities are needed. In addition, competing standards, for instance WiMAX (IEEE 802.16) (see section IV), were under development and the 3GPP was challenged by this competition. Furthermore the drop of prices for data delivery made it essential for the telecommunication companies (as key partners of 3GPP) to have a competing and efficient telecommunication network architecture. [11]

Fixed packet-switched networks have shown their capability to fulfill these requirements. Therefore an all-IP approach is consequential. With the LTE technology the mobile network operators are not required to maintain an additional complex circuit-switched domain. Current technologies, for instance SIP (Session Initiation Protocol) or IMS (IP Multimedia Subsystem) show that traditional services such as telephony or messaging can be established in all-IP networks reliably. These services provide also Quality-of-Service (QoS) mechanisms. As [12] shows LTE networks are superior to 3G/HSPA in terms of control plane scalability.

A. Architecture

A flat architecture is substantial to realize the main targets of LTE development. Hence this flat architecture require less nodes, which lead to lower delays and a higher reliability. Therefore 3GPP LTE Release 8 introduces only three different types of nodes. As prior telecommunication networks LTE divides these nodes into two different planes.

The SAE GW (System Architecture Evolution Gateway) operates in the user plane (UP), whereas the MME (Mobility Management Entity) is used in the control plane (CP). The eNodeB provides functionality in both planes. Basically, the LTE architecture consists of 4 different domains, as figure 4 shows.

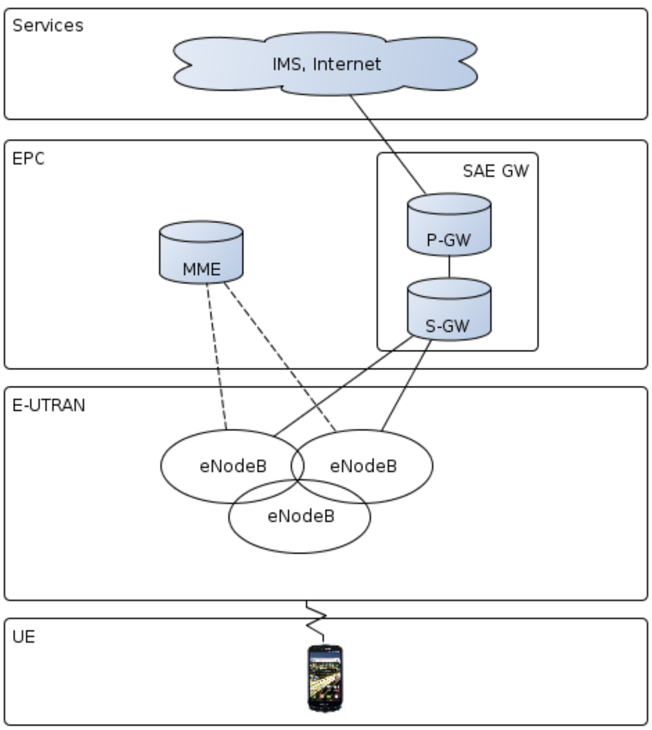

Figure 4. LTE System Architecture for E-UTRAN only, adapted from [11]

1) User Equipment Domain: The user equipment domain contains the UE (User Equipment) which is the device that connects the end user to the access network. The UE is usually a mobile device or a data modem.

2) E-UTRAN Domain: E-UTRAN (Evolved Universal Terrestrial Radio Access Network) is the access network of LTE. It contains the eNodeB (E-UTRAN NodeB) which is an enhanced base station. The eNodeB is a key entity with multiple roles in the LTE network.

First, it is the connection bridge between the EPC (Evolved Packet Core Network) and the UE. The eNodeB is responsible for the radio communication with the UE. In addition, it passes on the user plane data towards the core network entity (SAE GW), by ciphering/deciphering the IP data and compression/decompression of IP headers.

Furthermore, the eNodeB provides also functionality to the control plane. It is the responsible for the Radio Resource Management, which controls the usage of the radio interface in terms of resource allocation and traffic scheduling according to QoS.

At last, the eNodeB analyses UE-carried radio signals and makes measurements by itself for MM (Mobility Management) aspects. Based on these measurements it makes decisions to handover UE between cells. Additionally, handover signaling is also exchanged with the MME and other eNodeBs to provide routing information.

3) EPC Domain: The EPC provides the core network for LTE, which is only IP packet based. The EPC contains the nodes MME and SAE GW.

a) Mobility Management Entity (MME): The MME is the main control entity in the 3GPP LTE network. Furthermore, the MME is basically responsible for three functions, which are Authentication and Security, Mobility Management and Subscription Profile and Service Connectivity Management.

Authentication and Security: The UE is authenticated by the MME, to assure that it is who it claims to be. In this procedure the permanent identity of the UE is detected. Further, an authentication vector is asked from the Home Subscription Server (HSS) of the UE. The User Equipment is only authenticated, if the authentication vector is correctly repeated by the UE. This procedure is done with the first registration to the network and periodically to keep the authentication up to date. In addition, the MME allocates an unique temporary identity to avoid the permanent sending of the IMSI (International Mobile Subscriber Identity) over the air interface which protects the users privacy.

Mobility Management: The MME keeps track of the UE position either at the eNodeB level in active mode or at the Tracking Area (TA) level. The TA is a group of eNodeBs where the location of a UE is known in idle mode. Furthermore the MME is responsible to notify the HSS the current location of the UE. Based on the UE mode the MME is able to control the allocation and release of network resources. Finally, it is also involved in the handover of UE in active mode.

Subscription Profile and Service Connectivity Management: The subscription profile of the UE has to be retrieved by the MME. This profile contains information about the Packet Data Network access and whether certain services should be allocated. Additionally, the MME will set up the default bearer. Further service setups from dedicated bearers are also realized by the MME.

b) System Architecture Evolution Gateway (SAE GW): Another very important entity in the LTE network is the SAE GW, which operates in the user plane. The key function of the System Architecture Evolution Gateway is the transfer of the actual user data through the network. This includes data packets for VOIP, messaging or other Internet services. The SAE GW represents a combination of two gateways. The Serving Gateway (S-GW) and the Packet Data Network Gateway (P-GW). However, the interface and the operations between the two gateways have been specified. Therefore a separate deployment is possible.

Serving Gateway (S-GW): Basically the S-GW is responsible for the tunnel management and switching and is directly connected to the eNodeB. It controls only its own resources and allocates them upon request of the MME or the P-GW. The S-GW plays a major role in the active handover when the UE is in connected mode. The MME commands the S-GW a tunnel switch from one eNodeB to another. For idle mode the S-GW terminates the downlink (DL) data path and triggers the paging when DL data arrives.

Packet Data Network Gateway (P-GW): The P-GW is the connectivity point for the UE to external data packet networks. It provides highest level mobility support when a UE switches the S-GW. The Packet Data Network Gateway is also responsible for performing policy enforcement, gating and packet filtering. In addition, it collects and reports the charging information. Furthermore, a UE can connect to multiple P-GWs.

4) Services Domain: The services domain covers all services such as IMS (IP Multimedia Subsystem) or the Internet that are connected to the EPC.

B. Characteristics

LTE uses OFDM (II) and SC-FDMA in the physical layer which allows the deployment in different frequency ranges. OFDM allows the allocation of different-sized spectra with a large number of narrow-band subcarriers.

This is a very flexible approach and provides the opportunity to make further extensions. Since the digitalization of TV-signals more frequency bands can be used for telecommunication networks. Also the future shut-down of current telecommunication networks such as GSM or CDMA2000 releases distinct frequency bands which can also be used for LTE.

3GPP has defined that LTE will operate in both paired and unpaired frequency bands. Therefore LTE supports FDD (Frequency-Division Duplex) and TDD (Time-Division Duplex). FDD applies different carrier frequencies to the transmitter and the receiver. Whereas in TDD both uses one carrier frequency in different time slots. Obviously the paired frequency bands use FDD and the unpaired frequency bands use TDD. Table III shows the paired frequency bands defined by the 3GPP. The unpaired frequency bands are shown in table IV. Note that these frequency bands have to be shared among different mobile network operators. Parts of the frequency bands are assigned to distinct mobile network operators to avoid interference issues.

As stated before one of the main goals of the 4G telecommunication networks is the increase of the data transmission speed. The 3GPP has also defined different terminal categories. Table V shows the different terminal categories in LTE Release 8 and specific characteristics such as the approximate down- and uplink peak rates, the modulation and the use of multiple antennas (MIMO). All terminal categories have to support all RF (Radio Frequency) options from 1.4 MHz to 20 MHz.

Band	Uplink range (MHz)	Downlink range (MHz)	Main region(s)
1	1920-1980	2110-2170	Europe, Asia
2	1850-1910	1930-1990	Americas (Asia)
3	1710-1785	1805-1880	Europe, Asia
4	1710-1755	2110-2155	Americas
5	824-849	869-894	Americas
6	830-840	875-885	Japan
7	2500-2570	2620-2690	Europe, Asia
8	880-915	925-960	Europe, Asia
9	1749.9-1784.9	1844.9-1879.9	Japan
10	1710-1770	2110-2170	Americas
11	1427.9-1452.9	1475.9-1500.9	Japan
12	698-716	728-746	Americas
13	777-787	746-756	Americas
14	788-798	758-768	Americas

Table III
PAIRED FREQUENCY BANDS BY 3GPP FOR LTE (FDD) [10]

Band	Frequency range (MHz)	Main region(s)
33	1900-1920	Europe, Asia (not Japan)
34	2010-2025	Europe, Asia
35	1850-1910	-
36	1930-1990	-
37	1910-1930	-
38	2570-2620	Europe
39	1880-1920	China
40	2300-2400	Europe, Asia

Table IV
UNPAIRED FREQUENCY BANDS BY 3GPP FOR LTE (TDD) [10]

Terminal category	1	2	3	4	5
Peak rate downlink (Mbps)	10	50	100	150	300
Peak rate uplink (Mbps)	5	25	50	50	75
Modulation downlink	64QAM	64QAM	64QAM	64QAM	64QAM
Modulation uplink	16QAM	16QAM	16QAM	16QAM	64QAM
MIMO	Optional	2 x 2	2 x 2	2 x 2	4 x 4

Table V
TERMINAL CATEGORIES [11]

In addition to high data rates also low delays are desirable for 4G telecommunication networks. Certain requirements has been adopted for LTE in the control plane and the user plane. There are two measurements in the control-plane which measures the time that the terminal needs to change from a non-active state to an active state where the terminal is able to send or receive data. Depending on the non-active state this should not exceed 50 ms and 100 ms. In the user-plane the latency will be measured by sending a small IP packet from the terminal to the RAN (Radio Access Network) edge. This time should not exceed 5 ms. [10]

In networks such as GSM/UMTS a circuit-switched domain assured the QoS (Quality of Service) in telephony services. Therefore high delays in the packet-switched domain are not a big issue in terms of these services. To assure an equivalent QoS for LTE Release 8, which is only IP-packet based, low delays in the network are substantial. Telephony quality is not only measured by the delay time of data packets, but also by measuring the opinion of the actual user correlated with the certain delay times (Quality of Experience). A Study by Epitiro Ltd. [13] reveals that callers identify delays in the conversation when the round-trip delay exceeds 250 ms.

IV. Worldwide Interoperability for Microwave Access

WiMAX is a technology to provide wireless broadband access in multiple deployment scenarios. The standardization entity of this technology is the IEEE (Institute of Electrical and Electronics Engineers) lead by the 802.16 working group. In 2002 this group developed a line-of-sight operation standard, which used frequencies in the range of 11-66 GHz. Then in 2004 the IEEE 802.16-2004 (also 802.16d or Fixed WiMAX) standard was released, which offered point-to-point and point-to-multi-point operations. At the end of 2005 another standard (802.16-2005 or 802.16e) was approved which provided services to mobile terminals. This standard is well known as Mobile WiMAX. In this paper the focus is only on Mobile WiMAX Release 1.5, since the mobility support is a key feature of telecommunication networks. [14]

4G systems present new challenges and requirements in terms of spectrum limitations, architecture scalability and reliability or broad service abilities. Both next generation telecommunication networks meet these challenges with similar approaches. As LTE, WiMAX uses OFDMA for the wireless connection to its subscribers. In addition, the WiMAX network is based on a flat all-IP architecture.

A. Architecture

Because of its origin as a wireless transmission standard Mobile WiMAX defines only the MAC (Media Access Control) and the PHY (Physical) layer protocols. This covers among other things functions for network selection, mobility support, QoS signaling and management or power management. However, IEEE 802.16 does not have any support for a further End-to-End architecture. Therefore the WiMAX Forum [15], which ratifies the standards, set up the Network Working Group (NWG) that worked beyond IEEE 802.16 and developed the WiMAX End-to-End Network Architecture. There are certain similarities between the LTE architecture and the WiMAX architecture. As in LTE the WiMAX network architecture is an all-IP approach. As figure 5 shows, the high level WiMAX Network Reference Model (WiMAX NRM) differentiates between Network Access Providers (NAPs) and Network Service Providers (NSPs). A NAP provides radio access infrastructure. Whereas, the NSP provides IP connectivity and services to subscribers. The basic architecture consists of three logical entities.

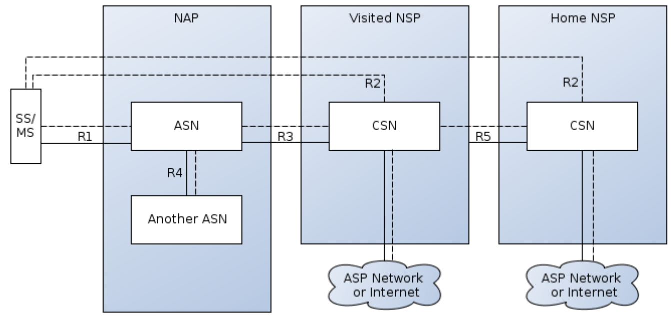

Figure 5. WiMAX Network Reference Model, adapted from [16], [17], solid lines: data bearer plane; dashed lines: control plane

1) Mobile Station: The Mobile Station (MS, often referred as Subscriber (SS) or User Terminal) is mobile equipment that provides wireless connectivity of one or more hosts to the WiMAX network. This approach is similar to the UE used in 3GPP LTE.

2) ASN: The ASN (Access Service Network) is the access network of WiMAX and therefore provides radio access to a MS. According to [18], the support of following functions is mandatory for all ASN:

- WiMAX Layer-2 connectivity to WiMAX MS
- Transfer of AAA (authentication, authorization, accounting) messages to Home NSP of a MS
- Network discovery and selection of MS's preferred NSP
- Relay functionality for establishing Layer-3 connectivity with a MS (e.g. IP address allocation)
- Radio Resource Management (RRM)

In addition, mobility support is handled in the ASN with these functions:

- ASN anchored mobility
- CSN anchored mobility
- Paging and Location Management
- ASN-CSN tunneling

Further extensions include also the QoS and policy management to ASN's functionality. Moreover, the ASN comprises of one or more Base Stations (BS) and one or more ASN Gateways (ASN-GWs) (see figure 6). Additionally, an ASN can be shared by multiple CSNs. The approach of the Access Service Network can be compared to the E-UTRAN access network.

3) CSN: Another entity of the WiMAX NRM is the CSN (Connectivity Service Network), which is responsible for the IP connectivity services of the WiMAX network. The WiMAX Forum [18] specifies also the following CSN functions:

- MS IP address and endpoint parameters for user sessions
- Internet access
- AAA proxy or server
- Policy and Admission Control based on subscription profiles
- ASN-CSN tunneling
- Inter-CSN tunneling for roaming
- Inter-ASN mobility

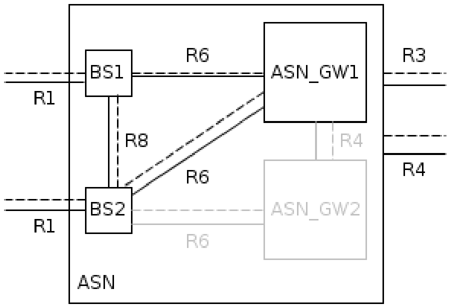

Figure 6. Reference Model of ASN decomposed in BS and ASN GW entities [16]

- Connectivity to services, such as IMS, Location-based services or provisioning

4) Reference Points: The reference points (R1-R5), as shown in figure 5, are logical interfaces for the protocol implementation between the WiMAX entities. The WiMAX NRM defines them as follows [16]:

- R1: Protocols and procedures between the ASN and MS. The covered Layers are PHY, MAC and Layer-3 control and management
- R2: Protocols and procedures between the MS and CSN mainly associated with authentication, authorization and IP host configuration.
- R4: Control and Bearer plane procedures between ASNs such as RRM, MS mobility across ASNs and idle mode/paging. This reference point serves as the interoperability RP across ASNs.
- R3: Control plane protocols (for AAA, policy enforcement and mobility management) as well as IP Bearer plane (necessary tunneling) between the ASN and CSN.
- R5: Control and Bearer plane protocols needed to support roaming between CSNs operated by a Home NSP and that operated by a Visited NSP.

These following reference points are defined within an ASN:

- R6: Includes all control and bearer plane protocols between the BS and the ASN-GW. The control plane consists of QoS, security and mobility-related protocols such as paging and data path establishment. The bearer plane represents the intra-ASN data path between the BS and the ASN-GW.
- R7: Optional reference point separating decision and execution functions within a ASN-GW (not shown in figures)
- R8: Optional reference point between BSs to ensure fast and seamless handover through direct and fast transfer of MAC context and data between involved BSs.

B. Characteristics

There are certain similarities between the characteristics of Mobile WiMAX and LTE. Mobile WiMAX uses OFDMA in the physical layer. At first, only TDD was supported by Mobile WiMAX. However further development resulted in the support of FDD for the varying frequency bands, which allows higher data rates. The high frequency bands (11-66 GHz) used in Fixed WiMAX are well applicable for fast last mile data delivery. On the contrary, in order to provide a better deployment of the Mobile WiMAX access network lower frequency bands are desirable. Mobile WiMAX does not have an unified global licensed spectrum. However, the WiMAX Forum has published several licensed spectrum profiles, which are shown in table VI. In addition, frequency bands below 700 MHz are under current consideration. This shall standardize equipment and lead to decreasing costs for manufactures.

Licensed Frequency Bands (GHz)	Regions
2.3 and 2.5	USA
2.5 and 3.5	Europe
2.3 , 2.5 , 3.3 and 3.5	South East Asia
3.5	Middle East
3.5	Africa
2.5 and 3.5	South/Central America

Table VI
REPORTED FREQUENCY BANDS USED FOR WIMAX [19]

As the underlying air interface technologies (e.g. OFDMA, MIMO, 64QAM) of Mobile WiMAX and LTE are very similar the key performance parameters are comparable. For this reason also delay times of Mobile WiMAX are similar to LTE. Table VII shows the peak rate comparison of both standards.

	LTE Release 8		WiMAX Release 1.5	
Duplex	FDD		FDD	
Channel Bandwidth	2x20 MHz		2x20 MHz	
Uplink Access	SC-FDMA		OFDMA	
Downlink Access	OFDMA		OFDMA	
BS Antenna	(2x2) MIMO		(2x2) MIMO	
Downlink Modulation	64QAM		64QAM	
Downlink Peak Channel rate	144 Mbps		144.4 Mbps	
MS Antenna	(1x2) SIMO		(1x2) SIMO	
Uplink Modulation	16QAM	64QAM	16QAM	64QAM
Uplink Peak Channel Rate	43.2 Mpbs	72 Mbps	82.9 Mbps	138.2 Mbps
Link Layer / Handoff Latency	<5 ms / <50 ms		20 ms / 35 to 50 ms	

Table VII
PEAK RATE COMPARISON FOR LTE AND WIMAX, ADAPTED FROM [20]

Mobile WiMAX was developed with QoS in mind. The data handling in the MAC scheduler is determined by a set of QoS parameters. Furthermore, the architecture supports differentiated levels of QoS (per user or per service flow per user). Also it provides mechanism, such as bandwidth management or admission control. In addition, the architecture supports the implementation of policies as defined by operators on their Service Level Agreements (SLA).

V. DISCUSSION

The key drivers, architectures and characteristics of LTE and Mobile WiMAX were shown in section III and IV.

This section presents a comparison of both technologies. The discussion takes a look at different aspects that results by the design decisions that are shown in the previous chapters. These aspects are diverse and cover different fields such as scenarios, enterprise use, deployment and power consumption.

A. Scenarios

Previous packet wireless telecommunication networks were often only used for data transfer for mobile devices. With the shown high data rates and low delays the 4G networks can provide more services and therefore more use scenarios. Transferring data to mobile devices, telephony and messaging remain key elements of the deployed networks. Furthermore other scenarios are possible with this kind of architecture. With the introduction of LTE in Germany the local providers had to agree that they will provide rural areas with fast Internet connections over LTE. In addition, the first generation of WiMAX was designed to replace the fixed last mile connection to the access network. Therefore 4G networks can be considered as a competing technology for wired Internet access, especially in non-saturated areas, such as rural areas or emerging markets. Another use case is the Mobile Gaming which has become very popular in the recent years as mobile device performances have increased. However, many games are still designed for single-player usage because of high delays in mobile networks. With 4G networks lower delays and higher data rates are available, so that popular gaming schemes (MMORPG or Sport Games) can be implemented with multi-player support for mobile devices. Also IPTV can be considered as a future use scenario. A first test has already been done by the German TV-station WDR [21]. Both, LTE and Mobile WiMAX are equally capable to fulfill the demands on such scenarios because of the similar data rates and network architecture.

B. Enterprise Networks

A special use case for the 4G networks is the application as a mobile enterprise network. The dominating wireless technology in enterprises is currently WLAN (IEEE 802.11). However, it has basic drawbacks because it does not support QoS. Additionally, an enterprise network has special security requirements. As [22] summarizes both next generation approaches can be hosted and deployed as next generation mobile enterprise networks. The flat all-IP architecture, high capacity, wide range and the strong QoS support of both 4G networks meet the requirements of a reliable mobile enterprise network. However, in security side only WiMAX is applicable without any further extension. It supports the standard authentication protocols EAP_TTLS and EAP_TLS. LTE instead uses a different approach called AKA which only authenticate the IMSI and the SIM card key. In enterprise environments multiple security credentials such as identity, certificates and username/password are required. Therefore LTE needs an additional extension to meet the requirements of a mobile next generation enterprise network.

C. Deployment

Mobile WiMAX and LTE are both optimized for fast data packet delivery. Both 4G networks use a new architecture approach with an all-IP structure and OFDM/MIMO for the air interface. The several advantages of this approach has been shown in the previous chapters. However, the deployment of these new networks will take years to reach the current coverage level of 2G or 3G networks. Therefore it is crucial for the success of the next generation networks, that they provide compatibility to the older generations. Although the term Long Term Evolution indicates a evolutionary step from 3G to 4G, both next generation telecommunication network approaches are more revolutionary. This also leads to a lot of challenges regarding compatibility with circuit-switched networks. In addition, compatibility support has to be provided also in multi-mode mobile devices due to lack of coverage of the next generation networks within the first years of deployment. The deployment of each 4G network depends on the current used 2G or 3G network of the operator which were shown in section I. Therefore both approaches introduce different interfaces to integrate in current networks. LTE, for instance provides certain interfaces that connect the S-GW and the MME to the SGSN of the WCDMA/HSPA network. Also the deployment in non-3GPP networks, such as CDMA2000 or WiMAX is defined [10]. Mobile WiMAX as well provides these interfaces for interaction with and integration in other networks. They have been specified in [23] and [24] by the WiMAX Forum and provide integration in 3GPP or CDMA2000 networks. With these interfaces both technologies can provide seamless handover to other networks. Consequently, both next generation networks are well prepared for the integration in current networks.

However, another aspect in the deployment matter is the deployment cost of such a new network. Due to its early introduction and fixed deployment, WiMAX is currently superior to LTE in this aspect. The network components have been in the market for a couple of years now which leads to lower prices. Additionally, the first commercial mobile phones supporting Mobile WiMAX were introduced in end of 2008 in the Russian market [25]. The first LTE networks and mobile devices were able in early 2010. Finally, Mobile WiMAX allows a faster and more cost-effective deployment.

In addition to the compatibility and the cost-effectiveness a third aspect is very important for the 4G networks which is the third party (operators, manufacturers, governments) support. In this term LTE is superior. The 3GPP consists of 6 organizational entities [26] that cover thousands of third party members. This is also the reason why the introduction of Mobile WiMAX in the European markets was avoided. Most of the European operators use 3GPP GSM networks. However, the low costs and high availability of Mobile WiMAX is very interesting for emerging markets such as Asia (China, Korea, India) or South America that are not fully covered with high speed Internet access yet.

D. Power Consumption

Mobile devices have limited battery power. Most modern devices provide a relatively big touchscreen and Multi-Core processors which are very power consuming. Furthermore, as stated in section II the use of OFDM and MIMO leads to higher power consumption. Therefore it is crucial for the 4G telecommunication networks to provide efficient power management mechanisms. Both, LTE and WiMAX provide similar mechanisms for power conservation. While Mobile WiMAX introduces the sleep and the idle mode, LTE adopts the RRC_CONNECTED and RRC_IDLE states [27]. Figure 7 shows the power management modes mapping to different types of traffic. In addition, the mentioned modes and states represent typical traffic usage scenarios in next generation networks. The first block may represent a block of downloaded data, while the second block probably presents a VOIP conversation with typical speech pauses. Moreover, LTE uses also a more power-efficient access multiplexing scheme with SC-FDMA.

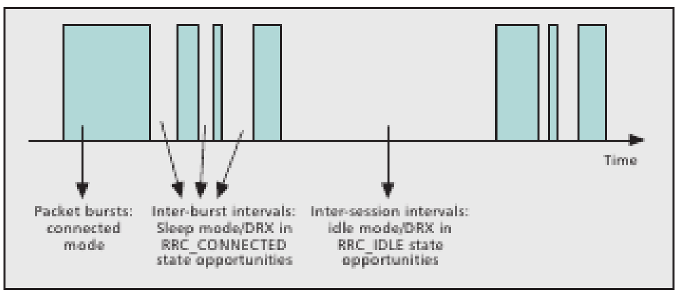

Figure 7. Mapping of power management modes to a generic traffic model [27]

However, a comparison [28] of power consumption shows that Mobile WiMAX is overall more power-efficient. Table VIII shows the power consumption of each technology considering also the power consumption of the access network's base station. In terms of power consumption of the "home devices" (mobile devices) both technologies are considered the same. In conclusion, Mobile WiMAX and LTE provide power management mechanism which allow a good power efficiency for the battery-operated mobile devices. However, LTE has a significantly higher power consumption in the access network which leads to higher operating costs for the operators.

	P_{home}	P_{access}	P_{total}
LTE	2.5 W	83.5 W	86 W
Mobile WiMAX	2.5 W	34 W	36.5 W
HSPA	2.5 W	462.3 W	464.8 W

Table VIII
COMPARISON OF THE POWER CONSUMPTION PER USER FOR LTE, MOBILE WIMAX AND HSPA, ADAPTED FROM [28]

VI. FUTURE TELECOMMUNICATION NETWORKS

The developing massive use of mobile services will lead to capacity issues also in the shown current approaches. Regarding this the future wireless telecommunication need to improve data rates, user capacities and latency rates. As stated before the ITU-R has specified the IMT-Advanced requirements [29] for 4G networks. 3GPP LTE Release 8 and Mobile WiMAX do not meet all of these requirements. However, the ITU has decided that the next evolution steps of LTE and Mobile WiMAX meet these requirements, namely 3GPP LTE Release 10 (also referred as LTE-Advanced) and Mobile WiMAX Release 2 (also referred as WirelessMAN-Advanced or 802.16m). These technologies are not yet ratified and therefore under development. The IMT-Advanced requirements, as shown in Table IX, cover several aspects of wireless telecommunication networks. Since the deployment of the current approaches recently started, it is not expected that the IMT-Advanced approaches will be implemented in the near future. However, as stated before LTE-Advanced and WirelessMAN-Advanced are evolutionary steps with the same architecture entities as the predecessors. This allows a continuous introduction in the future.

		IMT-Advanced
Peak Data Rate	DL/UL	1 Gbps
Peak spectrum efficiency (bps/Hz)	DL	15
	UL	6.75
Capacity (bps/Hz/cell)	DL	2.2
	UL	1.4
Cell edge user throughput (bps/Hz/cell/user)	DL	0.06
	UL	0.03
Latency	CP	100 ms
	UP	10 ms
Mobility/ Traffic channel link data rates (Bits/s/Hz)	120 km/h	0.55
Handover interruption times	-	-
-intra-frequency	-	27.5 ms
-inter-frequency	within spectrum	40 ms
	betw. spectrum	60 ms
Min. VOIP capacity (Active users/sector/MHz)	-	40
Channel Bandwidth		40 Mhz

Table IX
IMT-ADVANCED REQUIREMENTS, WITH ANTENNA CONFIGURATION 4X2 IN THE DOWNLINK (DL) AND 2X4 IN THE UPLINK (UL) [29]

VII. CONCLUSIONS

With 3GPP LTE Release 8 and Mobile WiMAX Release 1.5 the two competing 4G wireless telecommunication networks were shown. They have both very similar characteristics and an all-IP network approach. As shown in the discussion in section V both technologies provide sufficient solutions to the stated challenges. Furthermore, the discussion shows that Mobile WiMAX is superior to LTE in terms of security aspects in mobile enterprise networks. Also the deployment speed and the low costs are advantages for Mobile WiMAX. In addition, it is more power-efficient in the overall power consumption. Moreover, the current deployment and coverage of Mobile WiMAX is much higher.

However, the LTE deployment recently started and more and more operators choose the LTE/SAE architecture for their future wireless telecommunication network. The main reason for this is that the majority of operators uses 3GPP GSM or UMTS networks and participates, within the 3GPP, in the development of future 3GPP networks.

LTE-Advanced and WirelessMAN-Advanced provide future extensions to the current approaches. Therefore both technologies are assured of a good future. The competition scenarios are diverse and depend on the deployment region. For instance, in the USA there is a co-existence of both technologies. Sprint Nextel Corporation offers 4G properties over Mobile WiMAX to users, whereas Verizon Communications Inc. or AT & T Inc. provide 4G services with the LTE architecture. Also monopolies are established. LTE dominates the Western European market, whereas Mobile WiMAX is the only 4G technology in India. In conclusion, as in the previous generations of telecommunication networks there will be a global co-existence of LTE and Mobile WiMAX and their future developments.

References

[1] S. W. Ho, "Adaptive Modulation (QPSK, QAM)," Intel Corporation, Tech. Rep., 2004.

[2] S.-J. Lee, M. Goel, Y. Zhu, J.-F. Ren, and Y. Sun, "Forward Error Correction Decoding for WiMAX and 3GPP LTE Modems," in *Signals, Systems and Computers, 2008 42nd Asilomar Conference on*, oct. 2008, pp. 1143 –1147.

[3] A. Viterbi, "Error Bounds for Convolutional Codes and an Asymptotically Optimum Decoding Algorithm," *Information Theory, IEEE Transactions on*, vol. 13, no. 2, pp. 260 – 269, apr 1967.

[4] T. Giannopoulos and V. Paliouras, "Relationship among BER, power consumption and PAPR," in *Wireless Pervasive Computing, 2008. ISWPC 2008. 3rd International Symposium on*, may 2008, pp. 633 – 637.

[5] T. Harburg. (2006) Last access: June 15, 2011. [Online]. Available: http://www.et2.tu-harburg.de/Veranstaltungen/OFDM/2006/Pics/ofdm-spectrum1.gif

[6] blogial.com. (2009, 09) Last access : June 15, 2011. [Online]. Available: http://blogial.com/files/time-freq.jpg

[7] Conniq.com. Introduction to FDM, OFDM, OFDMA, SOFDMA. Last Access: June 18, 2011. [Online]. Available: http://www.conniq.com/WiMAX/fdm-ofdm-ofdma-sofdma-03.htm

[8] V. Bykovnikov, *The Advantages of SOFDMA*, Last Access: June 18, 2011, Intel Corporation Std., Rev. 1.1, 2005. [Online]. Available: http://my.com.nthu.edu.tw/~jmwu/LAB/SOFDMA-for-WiMAX.pdf

[9] J. M. Andreas Mitschele-Thiel, "3G Long-term Evolution (LTE) and System Architecture Evolution (SAE)," University Lecture, 2009.

[10] E. Dahlman, S. Parkvall, J. Sköld, and P. Beming, *3G Evolution - HSPA and LTE for Mobile Broadband*, second edition ed. Academic Press, 2008.

[11] H. Holma and A. Toskala, *LTE for UMTS - Evolution to LTE-Advanced*, second edition ed. John Wiley and Sons Ltd., 2011.

[12] G. Brown, "Control-Plane Scalability & Perfomance Requirements for 3G & LTE Networks," Heavy Reading, Tech. Rep., 2010.

[13] L. Epitiro, "LTE "Real World" Perfomance Study - Broadband and Voice over LTE (VoLTE) Analysis," 2011.

[14] K.-C. Chen and J. R. B. D. Marca, *Mobile WiMAX*. John Wiley and Sons Ltd., 2008.

[15] WIMAX FORUM. [Online]. Available: http://www.wimaxforum.org/

[16] P. Iyer, N. Natarajan, M. Venkatachalam, A. Bedekar, E. Gonen, K. Etemad, and P. Taaghol, "All-IP Network Architecture for Mobile WiMAX," in *Mobile WiMAX Symposium, 2007. IEEE*, march 2007, pp. 54 –59.

[17] "Mobile WiMAX - Part I: A Technical Overview and Perfomance Evaluation," WiMAX Forum, Tech. Rep., 2006.

[18] "WIMAX Forum Network Architecture," WiMAX Forum, Tech. Rep., 2011.

[19] V. Muntean and M. Otesteanu, "WiMAX versus LTE - An Overview of Technical Aspects for Next Generation Networks Technologies," in *Electronics and Telecommunications (ISETC), 2010 9th International Symposium on*, nov. 2010, pp. 225 –228.

[20] "WiMAX, HSPA+ and LTE - A Comparative Analysis," WiMAX Forum, Tech. Rep., November 2009.

[21] winfuture.de. (2009, 11) Last access : June 9, 2011. [Online]. Available: http://winfuture.de/news,51249.html

[22] L. Yi, K. Miao, and A. Liu, "A Comparative Study of WiMAX and LTE as the Next Generation Mobile Enterprise Network," in *Advanced Communication Technology (ICACT), 2011 13th International Conference on*, feb. 2011, pp. 654 –658.

[23] "WiMAX Forum Network Architecture - WiMAX - 3GPP Interworking," WiMAX Forum, Tech. Rep., 2008.

[24] "WiMAX Forum Network Architecture - WiMAX - 3GPP2 Interworking," WiMAX Forum, Tech. Rep., 2008.

[25] YOTA. [Online]. Available: http://www.yota.ru/en/htc_max_4g/main/

[26] 3GPP. [Online]. Available: http://www.3gpp.org/partners

[27] R. Kim and S. Mohanty, "Advanced Power Management Techniques in Next-Generation Wireless Networks [Topics in Wireless Communications]," *Communications Magazine, IEEE*, vol. 48, no. 5, pp. 94 –102, may 2010.

[28] M. Deruyck, W. Vereecken, E. Tanghe, W. Joseph, M. Pickavet, L. Martens, and P. Demeester, "Comparison of Power Consumption of Mobile WiMAX, HSPA and LTE Access Networks," in *Telecommunications Internet and Media Techno Economics (CTTE), 2010 9th Conference on*, june 2010, pp. 1 –7.

[29] ITU-R, "Requirements related to technical performance for IMT-Advanced radio interface(s)," ITU, Tech. Rep., 2008.